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ION SPECIFIC DIFFERENCES IN ENERGETIC FIELD ALIGNED UPFLOWING IONS AT 1 RE

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ABSTRACT

Measurements of energetic (0.5 to 16 keV) upward flowing ion distributions above the auroral regions from within broad structures that are associated with parallel electric fields below the satellite are presented. The pitch angle distributions of the two major ion species H+ and O+ were both field aligned as expected. However, the angul widths of the distributions and their dependence on energy were inconsistent with purely parallel acceleration: The H+ distributions became more strongly field aligned with increasing energy, while the O+ distributions became broader. The H+ ion distributions were characterized by a temperature anisotropy $T_{\perp} / T_{\parallel} \sim 0.1$, while the O+ transverse and parallel temperatures were comparable (1 keV). Within these regions the O+ ions were on the average a factor of 2 to 3 more energetic than H+. The mean energies of the H+ ions were substantially less than the potential drops below the satellite while the O+ ion energy corresponded more closely to the potential. Candidate interpretat ions include preferential perpendicular heating of the O+ component coupled with an H+ source and electric field- region extended in altitude and/or parallel energy loss processes acting primarily on the H+ beam.

INTRODUCTION

Within the topside auroral ionosphere from a few 100 km upward ambient ionospheric ions are commonly accelerated to energies ranging from a few eV to › 16 keV. The resultant upward flowing ions exhibit either field aligned (beams) [Shelley et al., 1976; Mizera and Fennell, 1977], or conical pitch angle distributions (conics) [Sharp et al., 1977,]. These observations imply the existence of two principally different classes of acceleration processes; one acting primarily parallel, the other transverse to the magnetic field direction.

Processes proposed to account for ion conics include wave particle interactions and perpendicular electric field structures with scale sizes of the order of or less than the ion gyroradius. Ion beams may have been generated by parallel electric fields but may in principle also have evolved from conical distributions through adiabatic transport from lower altitudes. This is not the case for the large majority of energetic (>0.5 keV) UFI beams observed at 8000 km altitude since they originated usually above >5000 km. For recent summaries covering the topics of ion acceleration and comprehensive lists of references see Ashour-Abdalla and Okuda [1983], Lennartsson [1983], Sharp et al. [1983].

Mass selective effects are a feature of many of the proposed mechanisms, and hence detailed studies of ion distributions may provide valuable information on the nature of these acceleration processes. Morphological studies of auroral UFI's [Ghielmetti et al., 1978; Collin et al., 1981; Sharp et al., 1983] have indeed provided evidence that the two primary ion species have on the average different energy and pitch angle distributions. It is not immediately apparent from these however, whether the ions were affected differently by the same processes or whether the differences are more statistical in nature.

The present work describes the mass dependent features in upward flowing ions (UFI's) observed within spatially wide acceleration structures that show consistent evidence for parallel electric fields below the satellite. For this purpose near simultaneous measurements of the energy- and pitch angle-distributions of upflowing H+ and O+ ions are examined and intercompared. This limited initial study focuses on three broad parallel electric field structures in which both ion species were present.

EXPERIMENT

The data used in this study were aquired by the Lockheed plasma composition experiment aboard the polar orbiting S3-3 satellite. Spin axis and experiment view directions were oriented such that a complete pitch angle scan to within about 5 deg of the magnetic field lines was obtained every spin period. The three ion mass spectrometers were operated at exponentially spaced energy level, hence simultaneosly acquiring a 3 point energy spectrum once per sec and approximately once every spin period the energy levels were stepped to one of four values thus covering the energy range from 0.5 to 16 keV in 12 steps once every 64 sec. Since a complete mass scan from 1 through 32 AMU/charge required 1 second, the two major ion species H+ and O+ were always sampled within 0.5 sec (~ 9° of rotation) of each other. In addition, four broad band electron spectrometers provided contiguous coverage of the energy range from 70 eV to 24 keV with temporal resolution of 0.5 seconds. The angular acceptances of both types of instruments were +-3 deg FW. More detailed descriptions of the instrumentation are available from Sharp et al.,[1979].

DATA SELECTION

The spin period of the satellite (~20 sec) corresponds at apogee to a horizontal distance of ~ 80 km. The resulting spatial and temporal resolution of the measurements is therefore inadequate to resolve any of the small scale features associated with auroras. To be able to recognize characteristic features in the pitch angle and energy distributions and to differentiate these from spatial and temporal variations it is necessary to combine measurements from several spins. This study will consequently be limited to spatially wide acceleration structures. In addition we require that the energy fluxes of both H+ and O+ UFI's peak well within the instrument energy range (0.5 to 16 KeV). To limit the study to parallel electric field acceleration regions, the simultaneous presence of enhanced upward loss cones in the electron fluxes is required.

About 50 acceleratation structures that meet the above criteria have been identified in a non comprehensive survey. The example selected for detailed presentation is of somewhat broader extent than usual but exhibits many of the typical features.

RESULTS

The event occurred on Aug 24, 1976 near the peak of a small magnetic storm (peak Dst =-45γ ,and Kp = 5+). At that time the spacecraft was crossing the northern auroral zone near the dusk LT meridian at an altitude of about 8000 km.

<u>Overview:</u> Figure 1 gives an overview of the upward flowing ion observations. In this energy versus time representation the intensity is encoded by means of black bars with the magnitude plotted parallel to the time axis. The width of a black bar is pro-

portional to the log of the count rate (~ energy flux), and its origin is placed at the location in time corresponding to the upward pitch angle direction. Each data point represents an unweighted average of the countrate over a 30 deg PA interval centered about the upward direction. Any contributions from isotropic fluxes were subtracted. As noted above the instrument performs simultaneous measurements at 3 different energies. Occasionally, when the energy-steping occured within the upward source cone additional sampling points became available. In Figure 1 only energy steps actually measured are displayed, and steps at which there was no response are drawn as a thin vertical line. As a guide to the eye, the energy steps at which the countrates peaked were connected by a thin line.

As seen from Figure 1 regions of UFI fluxes extended nearly contiguously from 69.7 deg ILA to 75 deg ILA. During most of this period both ion species (H+ and O+) were present with substantial fluxes that peaked at energies between 0.5 and 10 keV. Several structures can be discerned from Figure 1, each characterized by an increase followed by a decrease in the energy at which the peak fluxes occured (marked regions I–V in Figure 1). These modulations are consistently seen in both species and are suggestive of ion inverted V signatures.

Examination of the electron fluxes from this experiment revealed the presence of enhanced upward loss cones within each of the ion structures described above. Hence, except for spins during which UFI's were not observed a parallel potential drop was consistently present beneath the satellite [Cladis and Sharp, 1979]. Within the same regions, the electron fluxes exhibited pitch angle modulation signatures [Sharp et al.,1979] that are indicative of parallel electric fields above the satellite. To further verify the above observations we examined the energy–time spectrogram derived from the Aerospace ion and electron detectors for this pass. This experiment [Mizera and Fennell, 1977] which provided more detailed energy resolution shows several inverted V signatures in the electron fluxes that coincided with regions II, III, and IV. Similar correlations between the electron and UFI fluxes are described in Sharp et al., [1979]. We conclude therefore that parallel electric fields were present both below and above the spacecraft througout most of the ion acceleration structures of Figure 1.

Mean Ion Energy : The most striking feature in Figure 1 is the systematic difference in the peak energies of the two ion species. In order to quantify this difference, a flux weighted mean energy is calculated for each spin and ion species, from which a ratio of the mean energies is formed. The accuracy of such estimates from 3 point energy spectra is limited, however, model calculations using Maxwellian distributions indicate that reasonable estimates for the mean energy are obtained as long as the temperature is of the order of the mean energy, a condition that was generally satisfied during this of event. Depending on the particular set of energy steps in use, these averages either under- or overestimate the true mean. However, by averaging over all four combinations of energy steps these systematic differences are reduced substantially. In order to minimize these methodological uncertainties and to smooth out temporal/spatial variations the spin based ratios of the mean energies were averaged (relative error weighted) over each of the acceleration structures identified in Figure 1. The final uncertainties in these values are estimated to be less than 20 %.

An implicit condition for obtaining meaningful values for the average ion energy is that the bulk of the ion distribution fall within the measurement range of the instrument. This was not the case in regions I and IV, where the inferred potentials below the satellite were generally near the lower instrument threshold (0.5 keV), and where UFI's were primarily observed in the lowest energy channels. Consequently, further discussion will be limited to the three major acceleration structures.

Table 1 summarizes the average properties of the particles and potentials within these acceleration structures. As evident from this, the [O+/H+] energy ratios were significantly above unity, ranging from about 2 to 3. The most energetic upward flowing ions were seen to occur in region II. In regions III and IV, the typical H+ ion energies were close to the lower instrument threshold (0.5 keV) and as a result their average was probably overestimated. This suggests that the actual [O+/H+] energy ratios were somewhat higher than given in Table 1.

Angular Distributions : Figure 2 displays the pitch angle distributions observed in regions II and III . They have been assembled according to their energy into a low, medium, and high energy range. Although there is considerable scatter between curves from different spin periods one can nevertheless recognize some qualitative differences in the degree of field alignement. Both the H+ and the O+ distributions appeared to be field aligned (beams). The H+ distributions (Figure 1 a) are flatter at low energies, and more highly field aligned at higher energies. The shoulder at pitch angles > 30 deg at the highest energies is caused by the presence of an isotropic H+ component. In contrast, the O+ distributions are more field aligned at low energies and substantially wider at the higher energies. There is some evidence in the energetic O+ distributions for a plateau or a decrease at pitch angles < 20 deg. However, sampling resolution and counting statistics were insufficient to unambigously identify a possible conical component.

Energy-Pitch Angle Dependence: These above systematic energy dependences of the pitch angle distributions are further illustrated in Figure 3. In this, the FWHM of the H+ and O+ distributions are plotted as a function of energy. Values obtained from simultaneous measurements (during the same spin period) are connected by straight lines. Figure 3, more clearly shows the expected decrease in the angular width of the H+ distributions and the widening of the O+ distributions. In addition, it is evident that this tendency is indeed a feature of the "instantaneous" pitch angle distributions and not simply the product of random or sampling effects.

Magnitude of Parallel Potential: The magnitude of the parallel potential difference between the spacecraft and the ionosphere was determined from the electron loss cone enhancement. A detailed discussion of the methods applied are given in Sharp et al. [1979], and Cladis and Sharp [1979]. Estimates were derived for each half of the loss cone from each of the 3 more energetic electron detectors, from which an average was formed for that particular spin. A relative error weighted average of the ratio of the mean ion energy to the potential difference below was then obtained for each region and ion species. These average ratios together with the average magnitude of the potential below the spacecraft are included in Table 1. One sees from this that the H+ ratios were substantially less than unity and near or slightly above unity for O+ in all three structures. The uncertainties in the estimates of the potential differences may be somewhat larger than indicated since unknown effects such as pitch angle scattering may in principle have introduced additional scatter and biases. However, since the values obtained from all electron detectors were usually in good agreement these effects are insufficient to account for the low relative H+ energy. Note that the mean ion energies do not take into account the details of the pitch angle distributions. Proper weighting by solid angle would tend to further lower the H+ mean energy but increase the O+. The O+ relative energies are therefore consistent with being somewhat larger than unity.

SUMMARY AND CONCLUSIONS

We have examined the upward flowing ion signatures from three broad acceleration structures that showed evidence for parallel electric fields below the satellite. Within all three regions the distributions exhibited evidence for complex mass dependent acceleration effects. The O+ ions were consistently more energetic than H+, and when averaged over individual structures, the O+ mean energies were a factor of two to three higher. It is not clear at the present time how representative these examples are. Previous statistical studies have yielded energy ratios of about 1.7 [Collin et al., 1981, Sharp et al.,1983]. However, these studies applied different selection criteria and did not aver age over wide acceleration regions.

In order to qualitatively illustrate what the different energy dependences of the H+ and O+ UFI distributions imply in velocity space we provide in Figure 4 a set of phase space density contours. Note that these were not derived from individually measured data points, but were constructed from a fit to the parallel energy distributions observed in region II, and from smoothed pitch angle distributions (Figure 2) with energy dependent FWHM's derived from Figure 3. Included in Figure 4 are the estimates for the character istic temperatures inferred from the energy and pitch angle spectra. The elongated contours representing the H+ ion beam imply a population with a relatively high parallel ($\sim$ 0.6 keV) and low perpendicular temperature ($\sim$0.1 keV). In contrast, the O+ contours became progressively wider with increasing velocity and represent a population with high parallel and perpendicular temperatures.

The high perpendicular temperature of the O+ ions evidently requires a transverse heating process (to $T_{\perp}\sim$1.5 keV). If an ion conic resulted from this transverse heating near 5000 km altitute as suggested in [Ghielmetti et al.,1978; Gorney et al.,1981] and was subsequently accelerated at a higher altitute by the parallel electric field (5 kV, Table 1) of region II (Figure 1), it would give rise to the distribution of Figure 4 at 8000 km altitude. Hence the O+ ion beam observations are consistent with a two-stage acceleration process similar to the one described by Klumpar et al. [1984] and Collin et al. [1986].

In this scenario the O+ ions were accelerated through the full parallel potential difference after having been heated transversly. As a result the ratio of the final mean energy to the potential drop is expected to be substantially higher than unity [see Kaufmann et al., 1976]. In the examples presented here this ratio was near unity. This suggests that the O+ ion beam may have been unstable and lost a part of its streaming energy.

A principal difference between the H+ and O+ ion populations is the temperature anisotropy (Figure 4). In the case of H+ this implies that the high parallel temperature did not originate through perpendicular heating. This suggests that the ion beam was thermalized primarily in the parallel velocity direction, perhaps via an ion beam instability [Kintner et al., 1979] that may also have led to a net loss of parallel energy. Evidence for similar processes have been presented by Reiff et al. [1986]. Alternate interpretations involve time varying electric fields and/or an H+ source region and electric fields that are distributed in altitude [Kaufmann et al., 1976]. A direct consequence of these models is a low relative energy for the H+ population both with respect to the O+ ions as well as with the potential drop.

The observed ion energies and temperatures imply preferential acceleration of the heavier ion component. This is predicted by wave particle interaction theories [Ashour-Abdalla and Okuda, 1983], and by structured perpendicular electric fields [Lennartson et al., 1983; Yang and Kan, 1983]. The results presented here provide new constraints on the auroral acceleration processes. Taken alone they are not adequate to unambigously confirm any one of the above suggested interpretations.

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TABLE 1: Average properties of upward flowing ions and electric fields within acceleration regions.

Region	Energy [keV] H+	Energy [keV] O+	Energy Ratio [O+/H+]	Potential Drop kV	Energy/(Pot drop) [H+/ϕ]	Energy/(Pot drop) [O+/ϕ]
II	2.6 ± .2	4.8 ± .6	2.4 ± .4	5.4 ± .9	0.47 ± .05	0.98 ± .17
III	1.1 ± .1	2.5 ± .2	3.0 ± .4	2.1 ± .3	0.39 ± .04	1.24 ± .15
IV	1.1 ± .1	1.9 ± .2	2.1 ± .3	1.7 ± .4	0.58 ± .07	1.05 ± .12

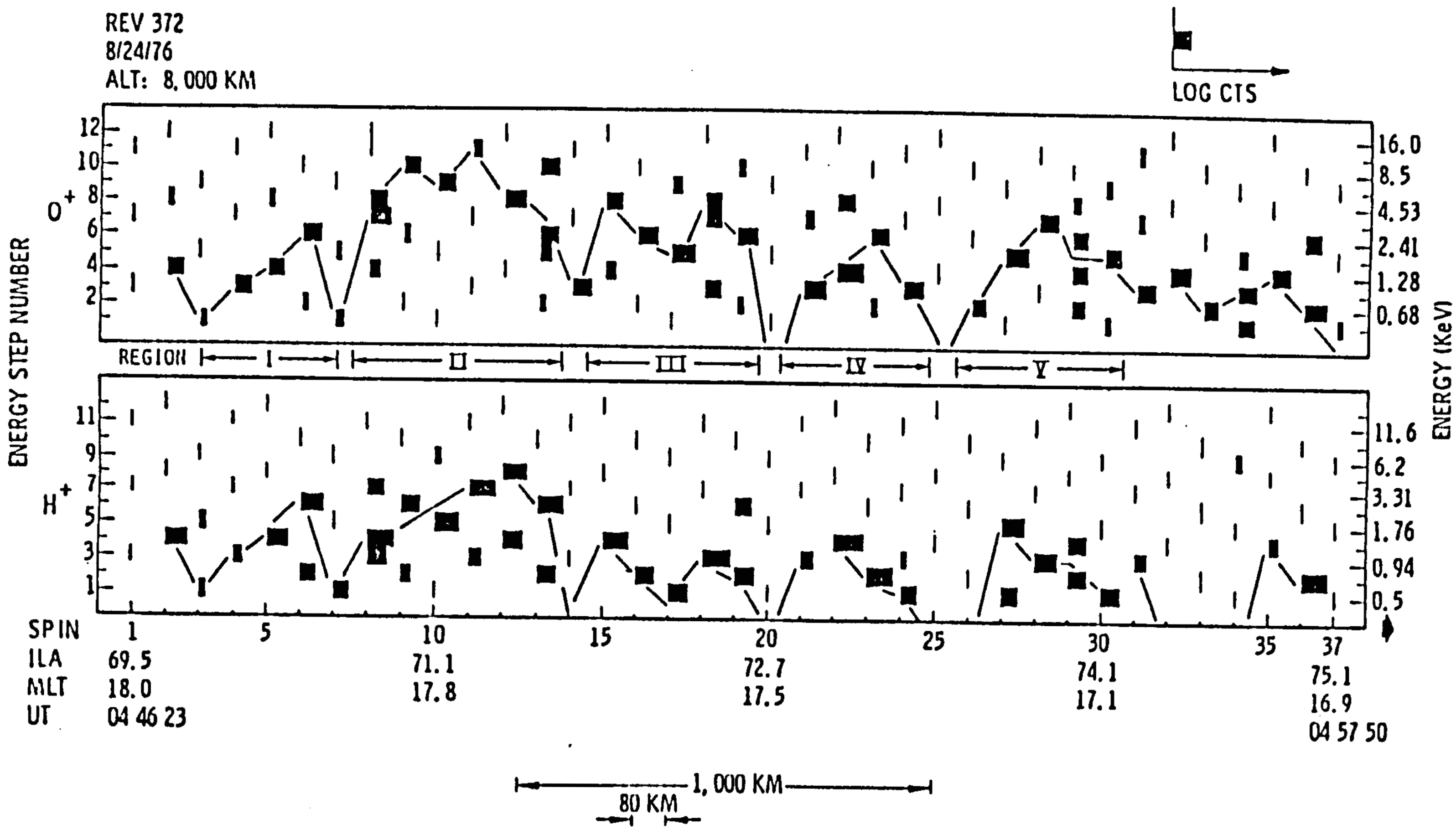

Figure 1 : Energy versus time representation of upward flowing ion flux intensities for auroral zone pass on Aug 24 1976. Count rates were averaged over a 30 deg upward pitch angle interval and are encoded by a black barr extending to the right hand side.

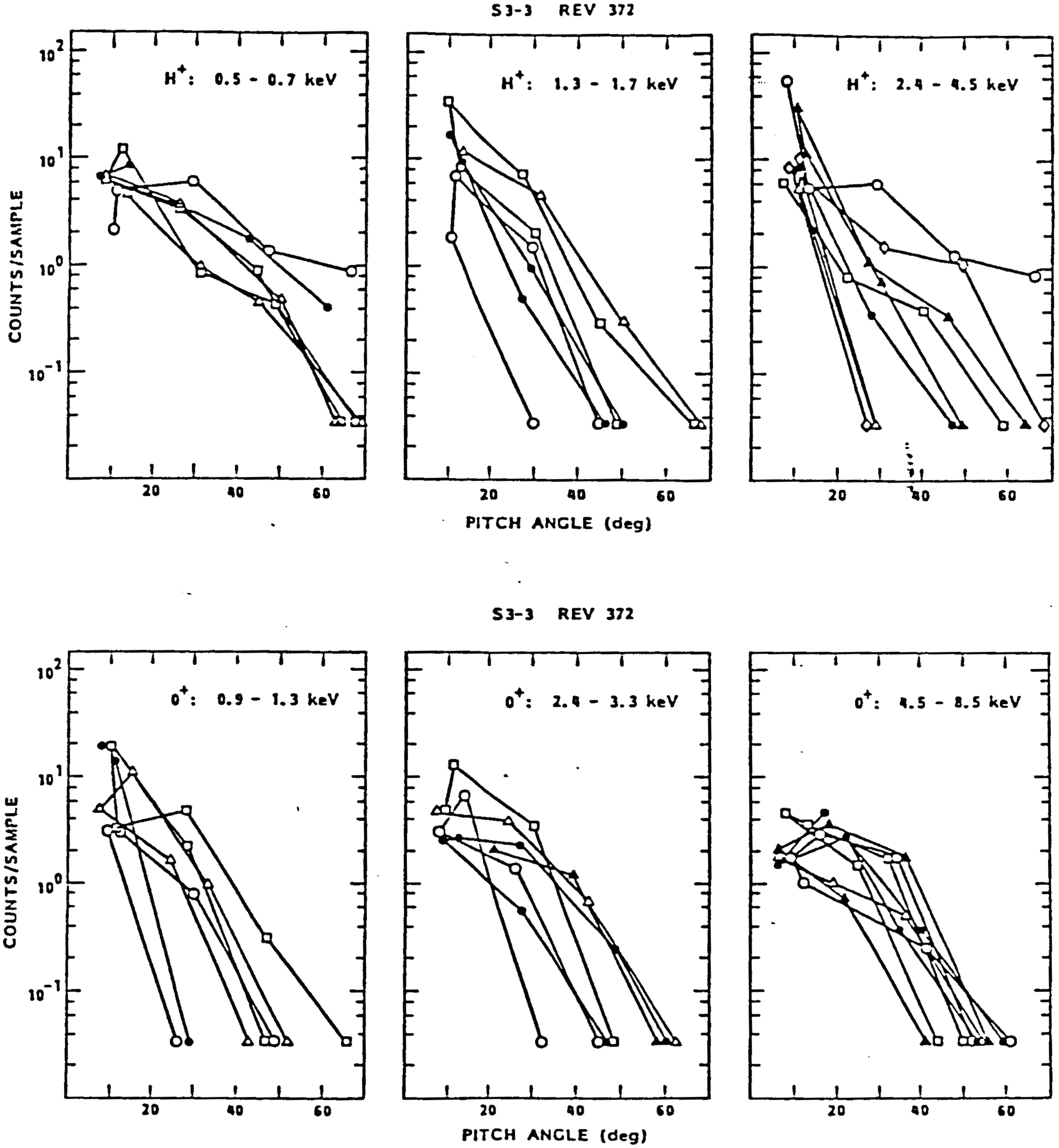

Figure 2 : Pitch angle distributions of H+ (top pannel) and O+ ions (bottom panel) grouped into three energy ranges for acceleration regions II and III. Inbound and outbound legs are plotted along the same axis. Different symbols indicate data obtained on different spins.

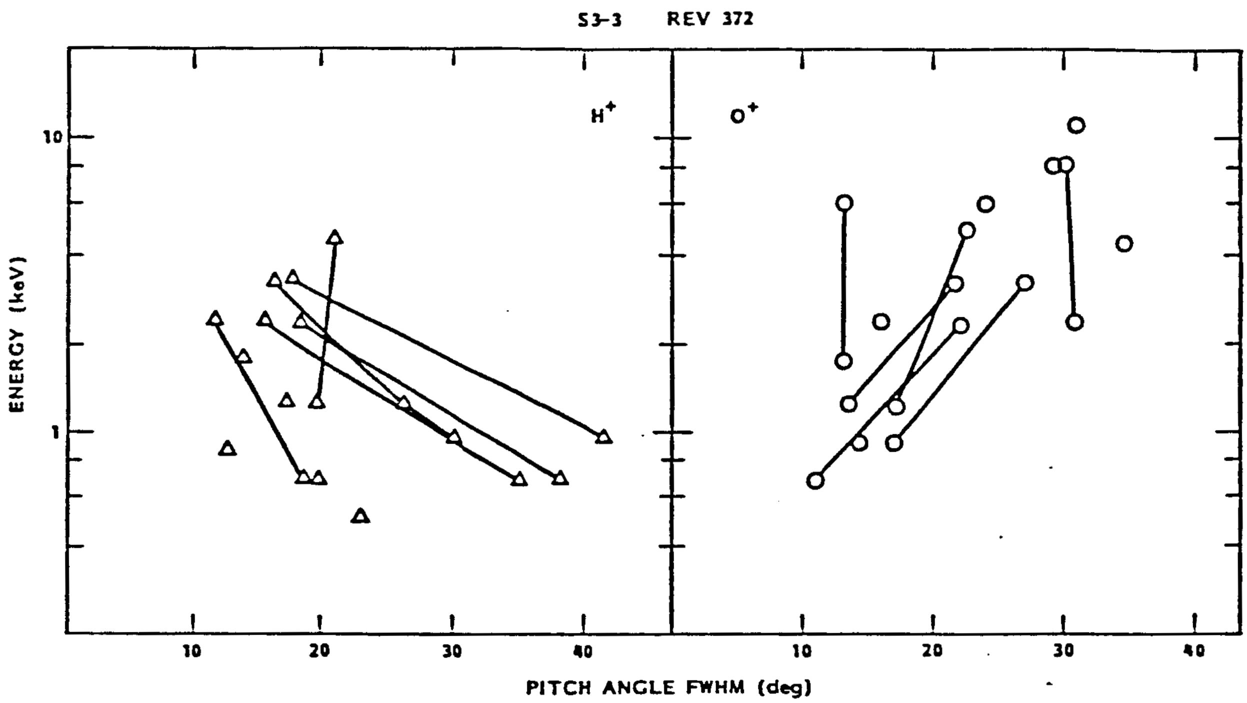

Figure 3 : Full width at HM of pitch angle distributions observed in regions II and III as a function of energy. Data points determined from simultaneous measurements are connected by a straight line.

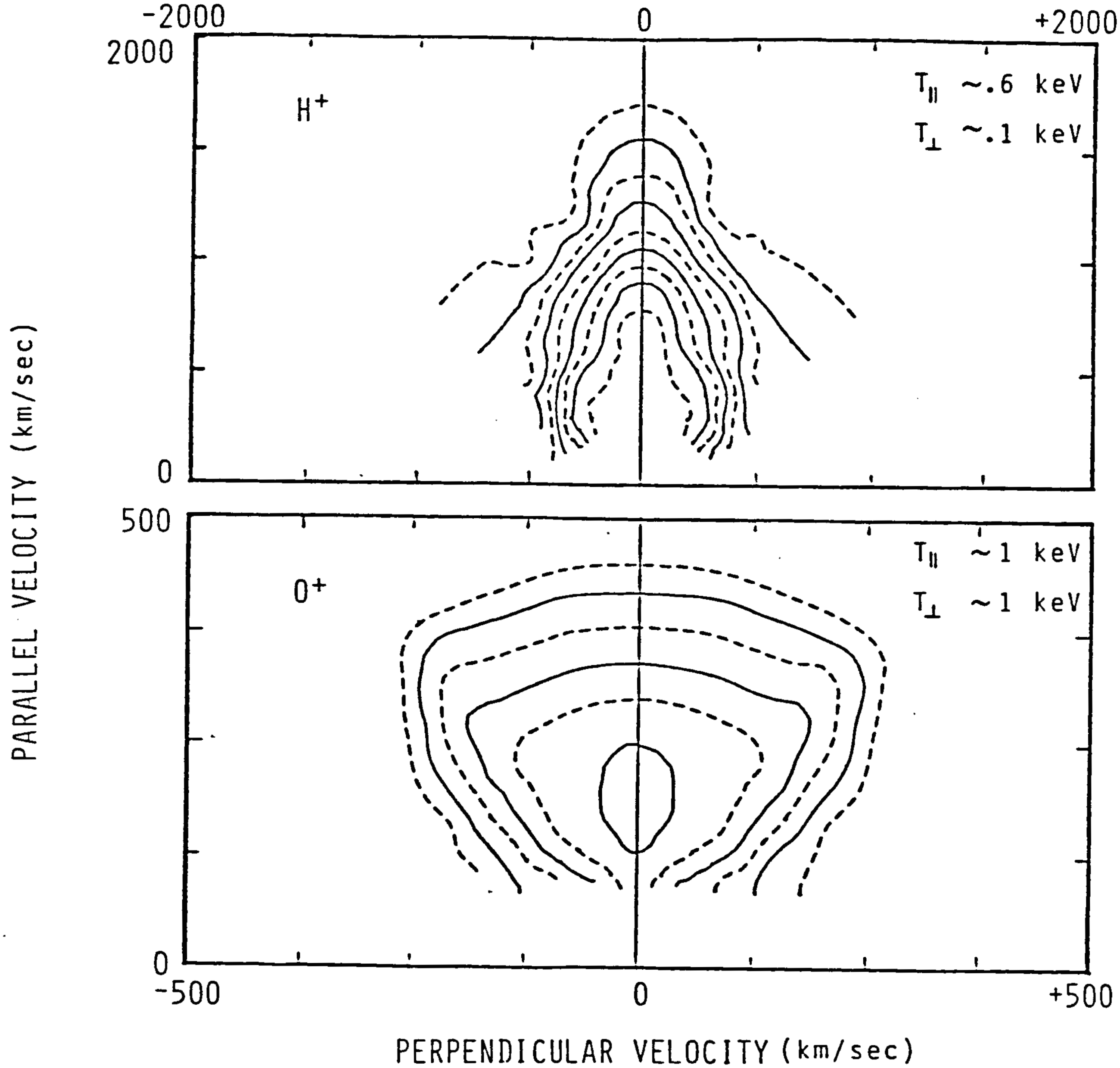

Figure 4 : Phase space density contours of H+ and O+ ion beams constructed from smoothed energy and angular spectras measured within acceleration region II.